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Permanent Superconducting Magnets for Space Applications

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(NASA-CR-196293) PERMANENT SUPERCONDUCTING MAGNETS FOR SPACE APPLICATIONS Final Technical Report, 1 May 1993 - 30 Apr. 1994 (Houston Univ.) 18 p

Abstract

We report progress during the period of the NASA grant, May 1, 1993 to April 30, 1994.

Work has been done to develop superconducting trapped field magnets (TFMs) and to apply them to a bumper-tether device for magnetic docking of spacecraft.

The quality parameters for TFMs are J_c, the critical current of the superconductor, and d, the diameter of the superconducting tile. During this year we have doubled d, for production models, from 1 cm to 2 cm. This was done by means of seeding, an improved temperature profile in processing, and the addition of 1% Pt to the superconductor chemistry. Using these tiles we have set increasing records for the fields permanent magnets. Magnets fabricated from old 1 cm tiles trapped 1.52 Tesla at 77K, 4.0T at 65K and 7.0T at 55K. The second of these fields broke a 17 year old record set at Stanford. The third field broke our own record. More recently using 2 cm tiles, we have trapped 2.3T at 77K, and 5.3T at 65K. We *expect* to trap 10T at 55K in this magnet in the near future.

We have also achieved increases in J_c using a method we developed for seeding U^{235}, and subsequently bombarding with neutrons. This method doubles J_c. We have not yet fabricated magnets from these tiles.

During this year we have increased production yields from 15% to 95%.

We have explored the properties of a magnetic bumper-tether for spacecraft. We have measured the bumper forces, and their dependence on time, distance, and the field of the ordinary ferromagnet (used together with a TFM). We have accounted for 85% of the collision energy, and its transformation to magnetic energy and heat energy. We have learned to control the relative bumper and tether forces by controlling TFM and ferromagnet field strengths.

I. Introduction

We have continued our studies of a new type of permanent magnet, the trapped field magnet (TFM). The principle of operation is that persistent supercurrents are established in a high temperature superconductor. These currents are trapped in place by faults in the superconductor. The faults are called pinning centers.

The TFM trapped field, B_t, has been shown[1,2] to be well approximated by

$$B_t \propto J_c f(d),$$

where Jc is the "critical" supercurrent, and d is the diameter of the current carrying region. f(d) is a complicated function of d, which monotonically increases with d[1].

During the past year we have worked to increase B_t by increasing J_c and d. We have also made significant progress on the design and laboratory testing of a device to act as a magnetic bumper and tether for two docking spacecraft (to soften any collision, and to tether the 2 craft together after they meet).

We work with modifications of the superconductor $YBa_2Cu_3O_7$ (Y123), which currently has the most desirable properties for TFMs.

II. Increases in B_t

A. Increases in Diameter, d.

In the work of this past year we have increased both the quality and reliability of the current carrying region.

We have introduced the use of $SmBa_2Cu_3O_7$ "seeds" into the growth process we use to produce Y123 tiles.

We have also modified the Y123 formula by introducing 1% Pt, and optimized the processing temperature profile.

These modifications have had a salutary effect on the usable tile diameter, d. Our production models of the magnets, which were 1cm in diameter at the start of this grant, are now 2 cm in diameter.

Dimensions larger than 2 cm have been achieved in experiments to further increase d. Such experiments had achieved 2.3 cm last year, and achieved 6 cm this year.

As a result of the above increases in d, we reported at the International Symposium on Superconductivity, at Hiroshima Japan [3], that we had achieved trapped fields of 1.52 Tesla at 77K, 4.0 Tesla at 65K, and 7.0 Tesla at 55K. See Fig. 1.

Previously the highest fields ever achieved in permanent magnets, 2.3T, had been reached by a Stanford University group in 1976[4]. Our trapped field of 4.0T at 65K broke that 17 year old record, and established a new world mark. With the achievement of 7.0 Tesla we set a newer world mark which broke our own record.

These fields, and the larger diameter, have outstripped our ability to activate and measure B_t in our own labs. We therefore designed and proposed, during this grant period, further testing at the National High Field Magnet Lab in Tallahassee. This proposal was accepted.

The usefulness of TFMs increases as the operating temperature increases. 77K is an attractive operating temperature, and can be achieved with liquid nitrogen at atmospheric pressure. 65K can be achieved with liquid nitrogen used at low pressure.

Most recently we have achieved trapped fields of 2.3T at 77K and 5.3T at 65K[5]. See Fig. 2.

These results again set records (at their respective temperatures), but more important, they markedly exceed the maximum fields obtainable with electromagnets (1.3 to 1.8T). Thus these TFMs now make motors and generators possible which are smaller, lighter, and more efficient than standard motors and generators. If we compare a motor using electromagnets at 1.3T, to one using the new magnets at, say, 3.9T, the 3-fold increase in field makes possible a *nine* fold decrease in weight.

The Emerson Electric Co., Motor Division, in St. Louis, MO., has collaborated with us to test a prototype generator, using our TFMs. In early 1994 this generator achieved an output of ~ 100 Watts. [6]

There are many other emerging applications for these trapped field magnets. They are usable for levitated transportation, bearings, flywheels, energy storage, etc. In Sec. III, we shall discuss our work on one of these applications, a bumper-tether for spacecraft.

B. Increases in J_c

We have studied improvement of the pinning centers which both hold the trapped field in place, and make possible higher J_c.

We had previously studied pinning centers created chemically, and created by bombardment with high energy light ions (p^+ and $3He^{++}$) at 200 MeV.

We are now engaged in a study of columnar shaped pinning centers [5,7], which hold promise of achieving higher J_c, and higher ultimate B_t. Both an IBM/ORNL group [7], and our group [5] have produced such centers using heavy (high Z), high energy ions.

The maximum B_t achievable with p, He pinning centers, in Y123 is 4-6T at 77K. Since we have already achieved over 2T, this appears as a looming limit to our work. However, Civale et al [7] have shown that columnar pinning centers double the maximum B_t achievable.

We are pursuing work with columnar pinning centers at 3 levels. First, we have an accepted experiment at the National Superconducting Cyclotron Lab (NSCL) in Lansing, Michigan to do a basic study of columnar centers as a function of Z and E of the bombarding ions. This will be done in the energy region of 6GeV. In effect this varies the rate of energy loss along the ion path, dE/dx, which in turn varies the diameters of the columns. The Civale[7] experiment shows the salutary results described above for dE/dx ~ 2000 eV/Angstrom. Our NSCL experiments will probe the dE/dx region 250-8000 eV per Angstrom, to seek an optimum. The calculations, proposal, and acceptance by NSCL were accomplished during this NASA grant.

Recent theoretical work at Harvard[8] indicates that there are further gains to be had by producing columns which are *not* parallel, and/or which vary randomly in the width of the columns. During this NASA grant we designed, proposed, and had accepted experiments at Brookhaven National Lab (BNL). Under the BNL proposal we will do several experiments in the 6 trillion electron volt Gold beam of the BNL Alternating Gradient Synchrotron (AGS). The beams of the AGS allow variation of angle and dE/dx in a nearly random way.

The NSCL and BNL experiments, scheduled for late 1994, were both developed under this NASA grant.

C. U^{235}

While doing basic studies at NSCL and BNL on columnar pinning centers, we are also pursuing a more practical production method for these centers. We add circa 25 parts per million of U^{235} to the Y123 mix. The U^{235} is dispersed in deposits $<<6\mu m$ in diameter, separated by $<20\mu m$. The Y123 + U is then bombarded with thermal neutrons (n°). (The BNL reactor will be used for future runs. The TAMU reactor was used for past runs). The thermal n° cause the U^{235} to fission, producing two high Z energetic ions with typical Z~46, and E_{TOTAL} ~ 200MeV. These fission fragments lace the Y123 with columnar defects. This is indicated schematically in Fig. 3 An SEM photomicrograph of the Uranium dispersion is shown in Fig. 4.

Because the U^{235} is dispersed very evenly, and the n° are very penetrating, this is a practical method for making large TFMs with columnar defects.

In our first test, this technique doubled J_c to 85000 A/cm^2 (See Fig. 5.)

We have not yet completed sizable magnets by this method, but the expected trapped field at 77K is $\geq$ 4.6T. We refer to this as the U/n° method.

The initial experiments were limited by the use of depleted U. The U used had only 0.4% U^{235}. The achievement of 25 ppm U^{235} required so much accompanying U^{238}, that the chemistry and processing used to produce excellent tiles was disrupted.

This problem is solved by using enriched uranium. We have now received 90% enriched U^{235} from the DOE. We have been accepted for thermal neutron irradiation at a BNL reactor. We will now be able to study the U/n method without chemical limits.

This particular subgroup of experiments is titled "Beating Swords Into Ploughshares."

III. Progress on Bumper-Tether for Spacecraft

TFMs possess some unique characteristics. The boundary conditions on the supercurrents, combined with Faraday's Law, produce the following behavior:

1. When an ordinary ferromagnet approaches an unmagnetized Y123 tile, the change in field induce currents in the tile via Faraday's Law. These currents produce a mirror image of the approaching magnet, which repels the approaching magnet. This behavior accounts for the "bumper" phase of our bumper-tether device.

2. When the approaching magnet retreats, the nature of the resulting current decrease in the TFM leads to a trapped field. The trapped field is in the *same* direction as that of the ferromagnet, and results in an attractive force.

Fig. 6 shows experimental results for three cases, $B_{Fe}<B_{t,max}$, $B_{Fe}\sim B_{t,max}$, and $B_{Fe}\sim 2B_{t,max}$ where B_{Fe} and $B_{t,max}$ are, respectively, the field of the ordinary ferromagnet, and the maximum trappable field of the superconductor.

We have learned that by controlling $B_{Fe}/B_{t,max}$, we can control the relative bumper and tether forces. The variation of relative bumper and tether forces is seen in Fig. 6 by the increasing lower "dip." This is the tether force. We understand this behavior on the basis of the Bean model of supercurrents.

Studies such as those shown in Fig. 6 have been done by developing the test rig shown in Fig. 7. The test tower has force and position transducers to perform measurements such as in Fig. 6. Both position and force transducers are interfaced to a computer. At present, temperature and magnetic field transducers are being added to the test tower to record all quantities of interest automatically.

The test tower also has motor drives of variable speed. Using this we have studied the dependence of the bumper force on approach velocity. We have observed that the bumper force increases as velocity of approach increases, which is useful. This is shown in Fig. 8.

We have related this time dependence of the bumper force to the phenomenon of "creep" in superconductors. Creep is expected to result in a decrease of field with time given by

$$B_t(t_2) = B_t(t_1)\,(1-\log[t_2-t_1])$$

This behavior results in a straight line plot of B_t vs. log (t_2-t_1) on a time scale logarithmic in t.

Fig. 9 is an early result for F_{bumper} vs. log t. The small deviations from a straight line are understood, and are due to artifacts such as effects of temperature changes on the force transducer.

Studies such as the dependence of force on velocity have enabled us to study how the energy is dissipated in a docking collision. At the outset of this year's work, we could only account for 14% of the collision energy. At present we can account for 85% of the collision energy, and can predict the rates of transformation of mechanical to magnetic to heat energy.

IV. Summary

During the past year:

•We have doubled the Y123 tile diameter for producing TFMs

•We have set new world marks for trapped field. These are now:

2.3 Tesla at 77K

5.3 Tesla at 65K, and

7.0 Tesla at 55K

•We have learned how to further double J_c using U^{235} seeding and thermal n° bombardment (not yet used in the above results).

•We have increased production line yields of TFMs from circa 15% to circa 95%.

•We have used TFMs, with the Emerson Electric Co Motor Division to produce a test generator with 100 Watt output.

•We have advanced the bumper-tether for spacecraft to produce clear demonstrations of the bumper force, the tether force, the increase in bumper force with approach velocity, and the increase in tether force with B_{Fe}/B_t. We have related the dependence of force on velocity to the fundamental phenomenon of creep. We have accounted for 85% of collision energy, and tracked it from mechanical to magnetic to heat energy.

V. References

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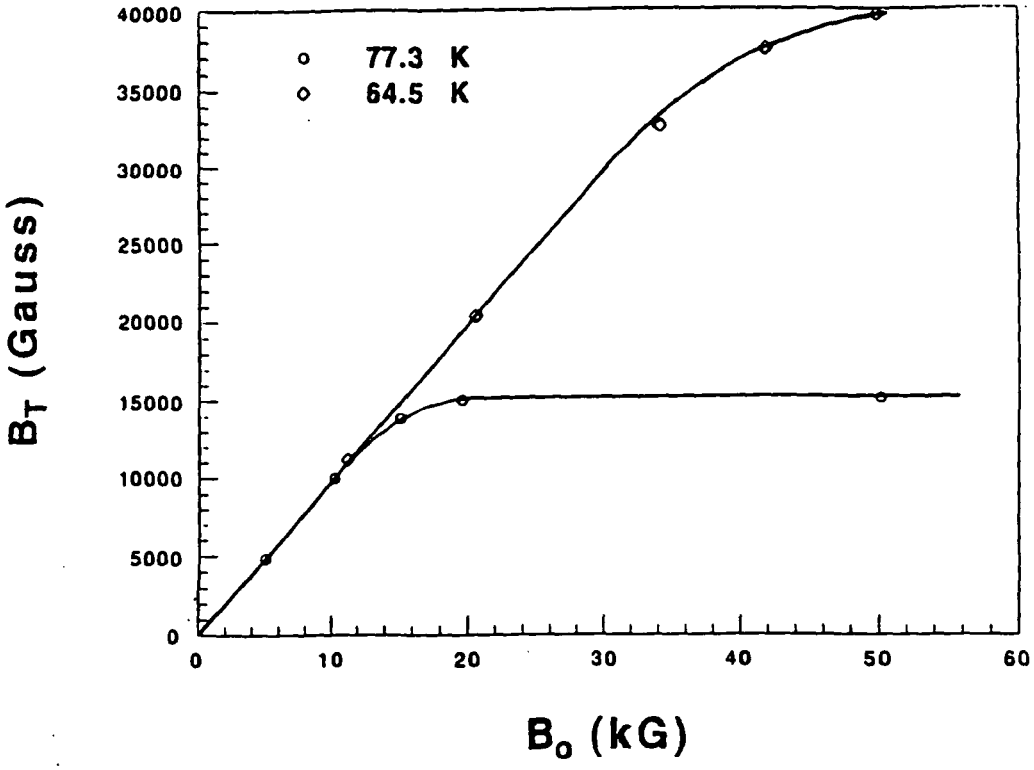


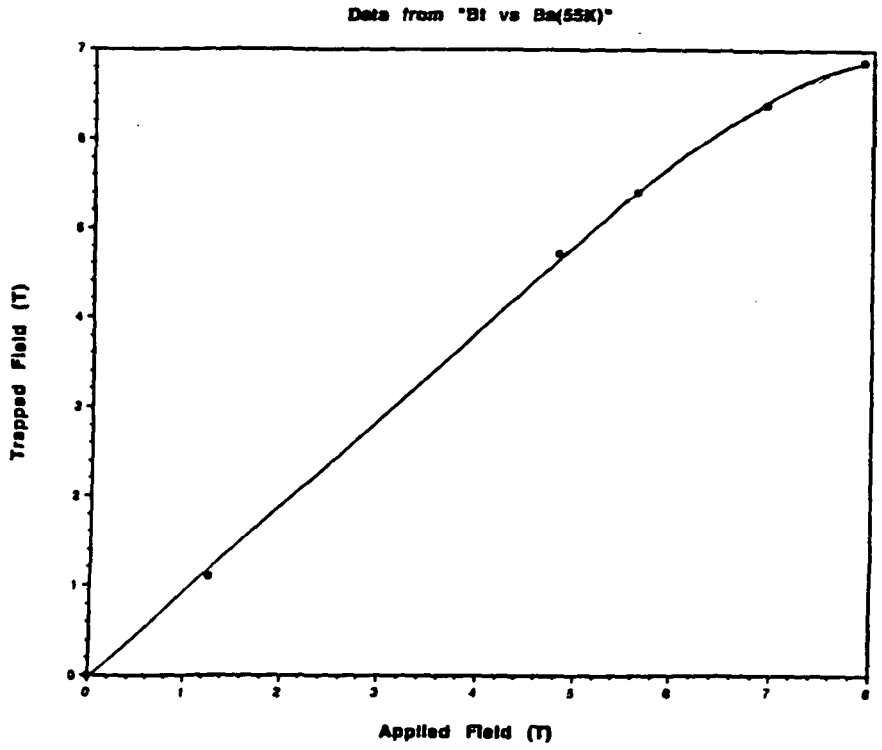


Fig1. Activation Data on Two Mini-Magnets. Top: Activation of an 8 tile mini-magnet at 77 K and 65 K. At each point the magnet starts warm. It is cooled in the Applied Field, B_0, and traps the field B_t. Bottom: Activation of an 8 tile mini-magnet at 55 K. Prior to this work, the highest quasi-stable permanent magnet was made at Stanford, in 1976, and trapped 2.3 Tesla. (M. Rabinowitz, et. al., Appl. Phys. Lett., 30 (11), 607 (1977).).

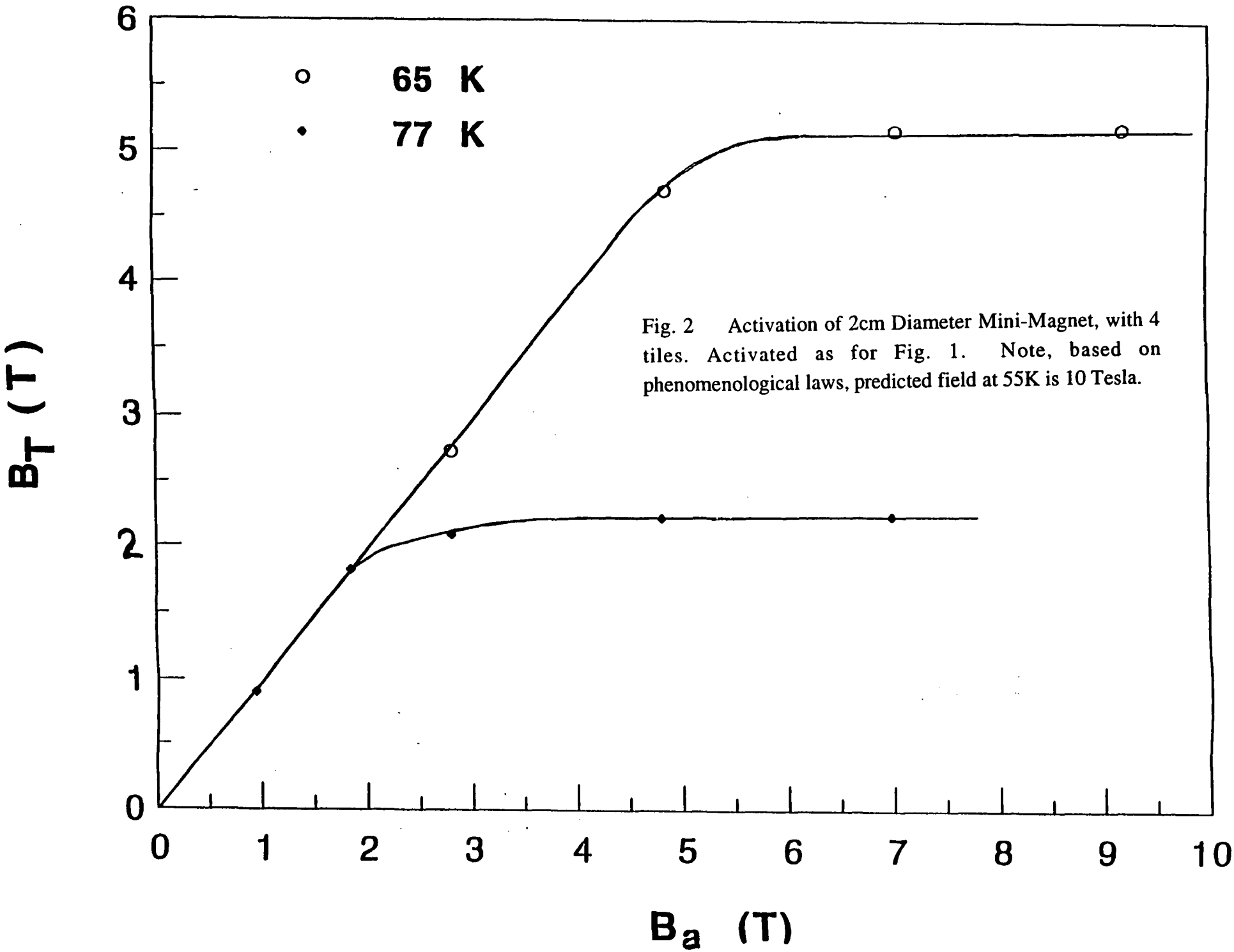


Fig. 2 Activation of 2cm Diameter Mini-Magnet, with 4 tiles. Activated as for Fig. 1. Note, based on phenomenological laws, predicted field at 55K is 10 Tesla.

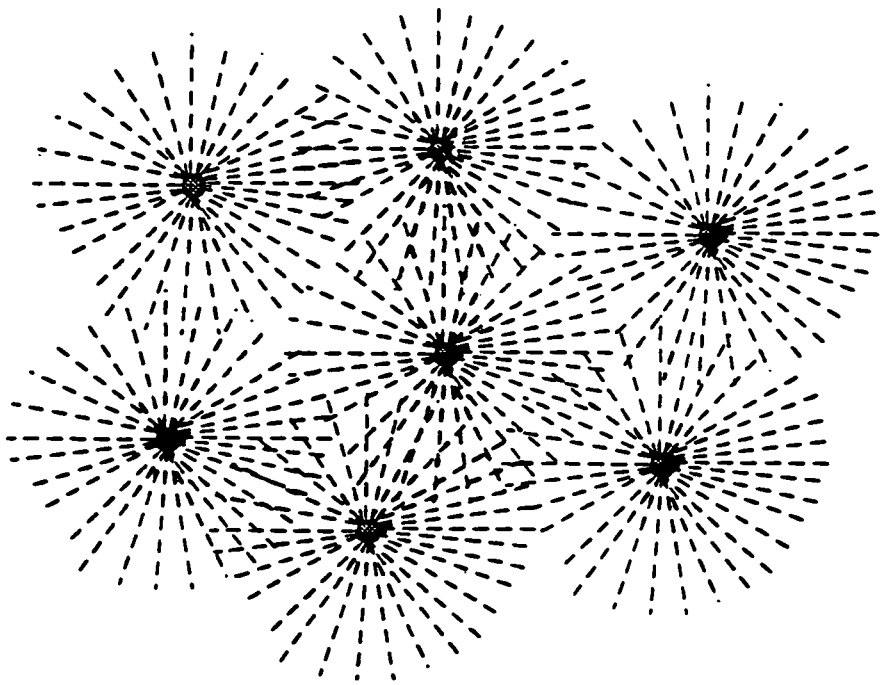
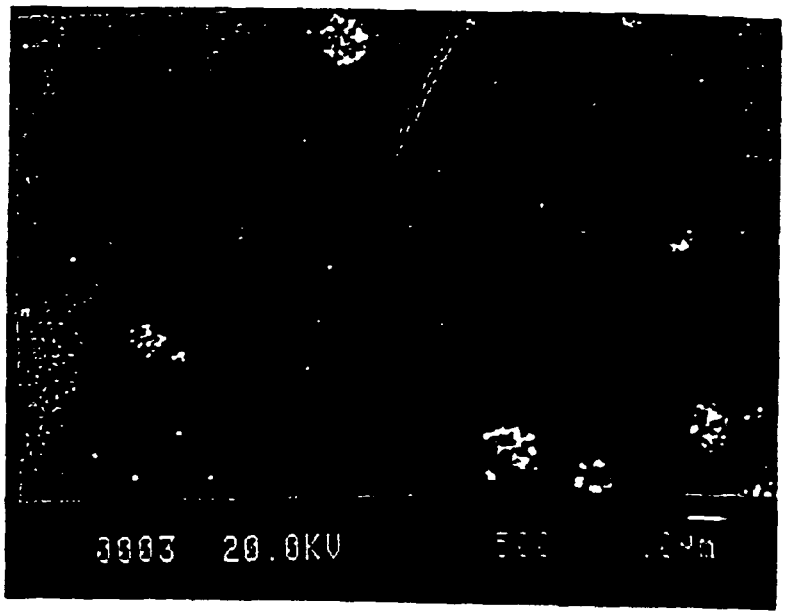


Fig. 3

Spacing needed << 20 μm

U size needed << 6 μm



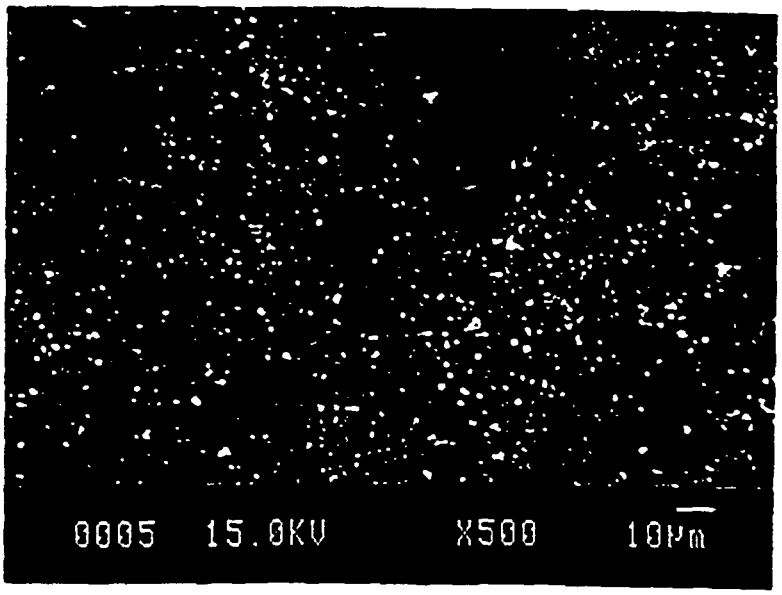


Fig.4. SEM Micrographs of MT Y123 + $U)_3$ (0.6% by weight). Top figure shows deposits of $(U_{0.4}Y_{0.6})BaO_3$ (light areas) with size comparable to range of fission fragments. Lower figure shows much smaller deposits after introduction of ball milling methods.

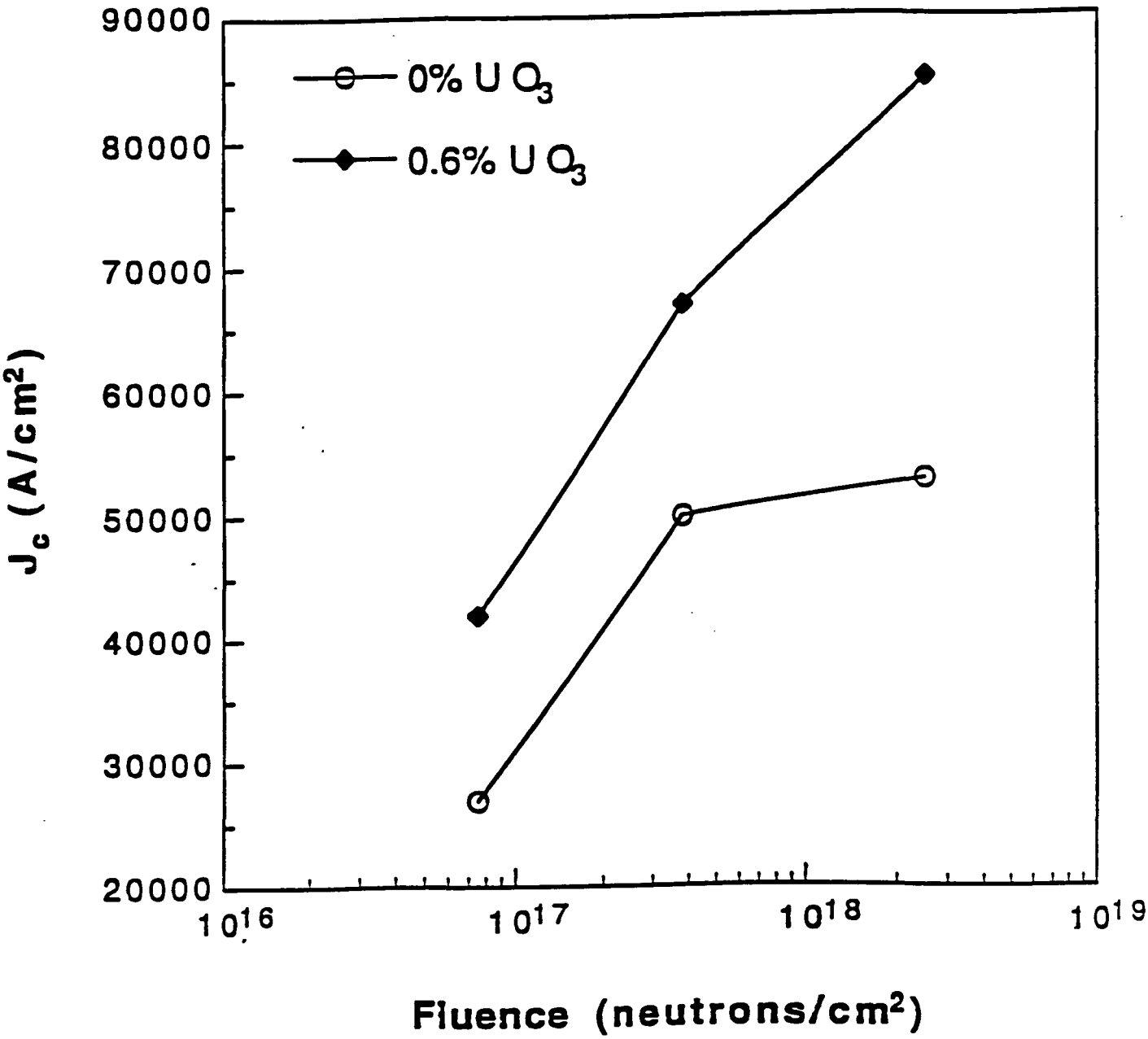
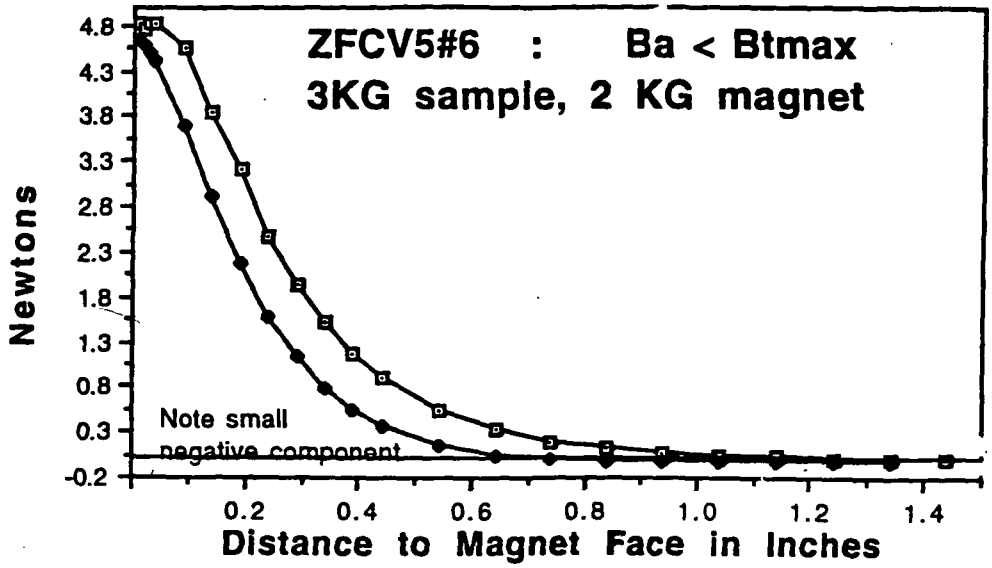
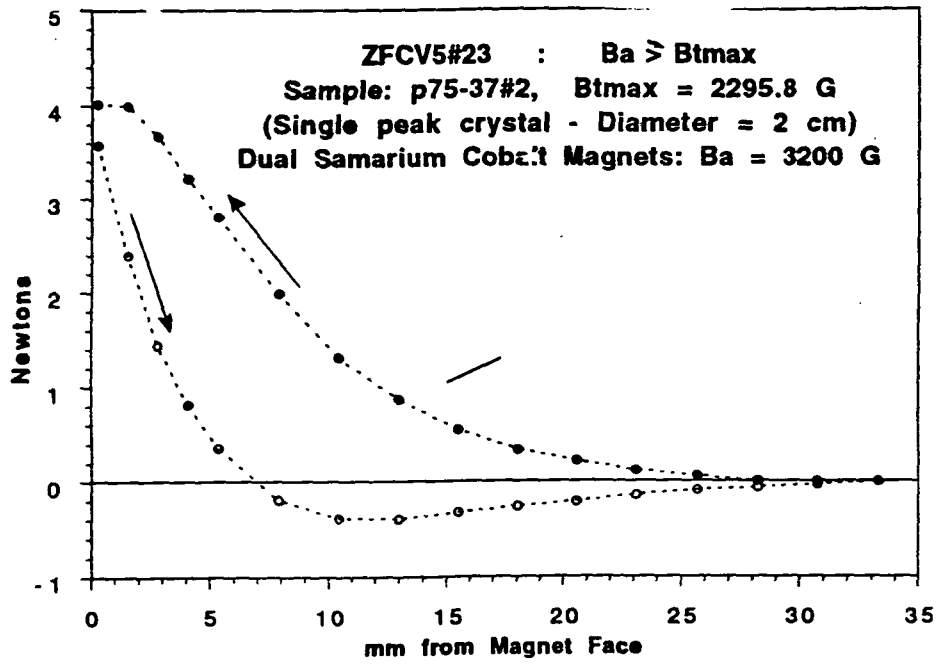
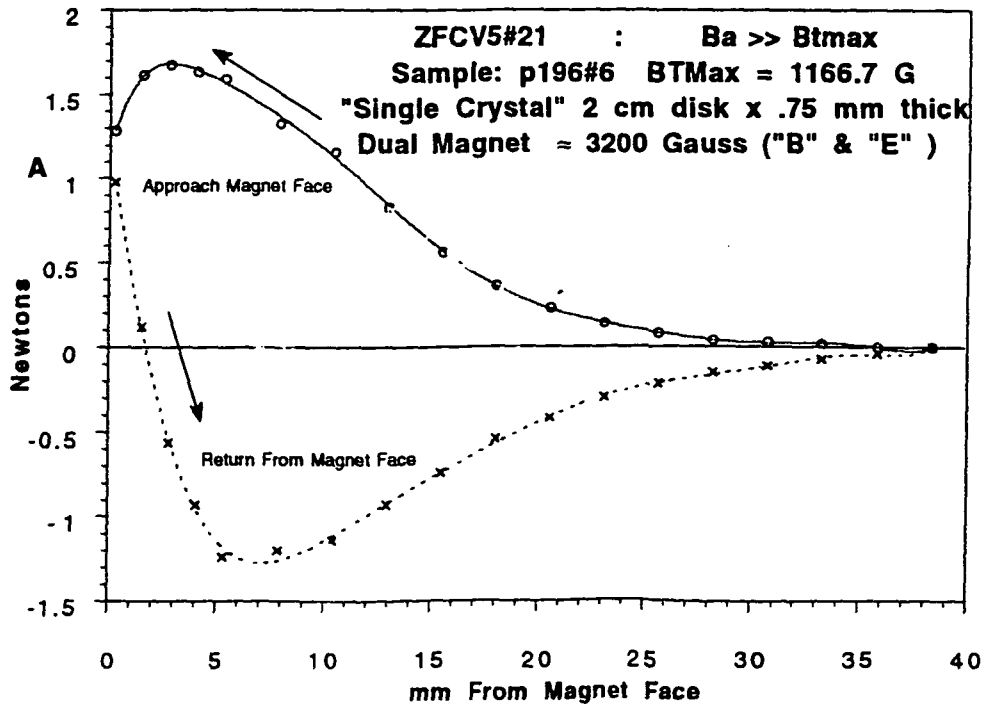


Fig. 5 J_C vs. # Neutrons/cm^2

Fig.6. Effects of the Ratio of Ba / Btmax







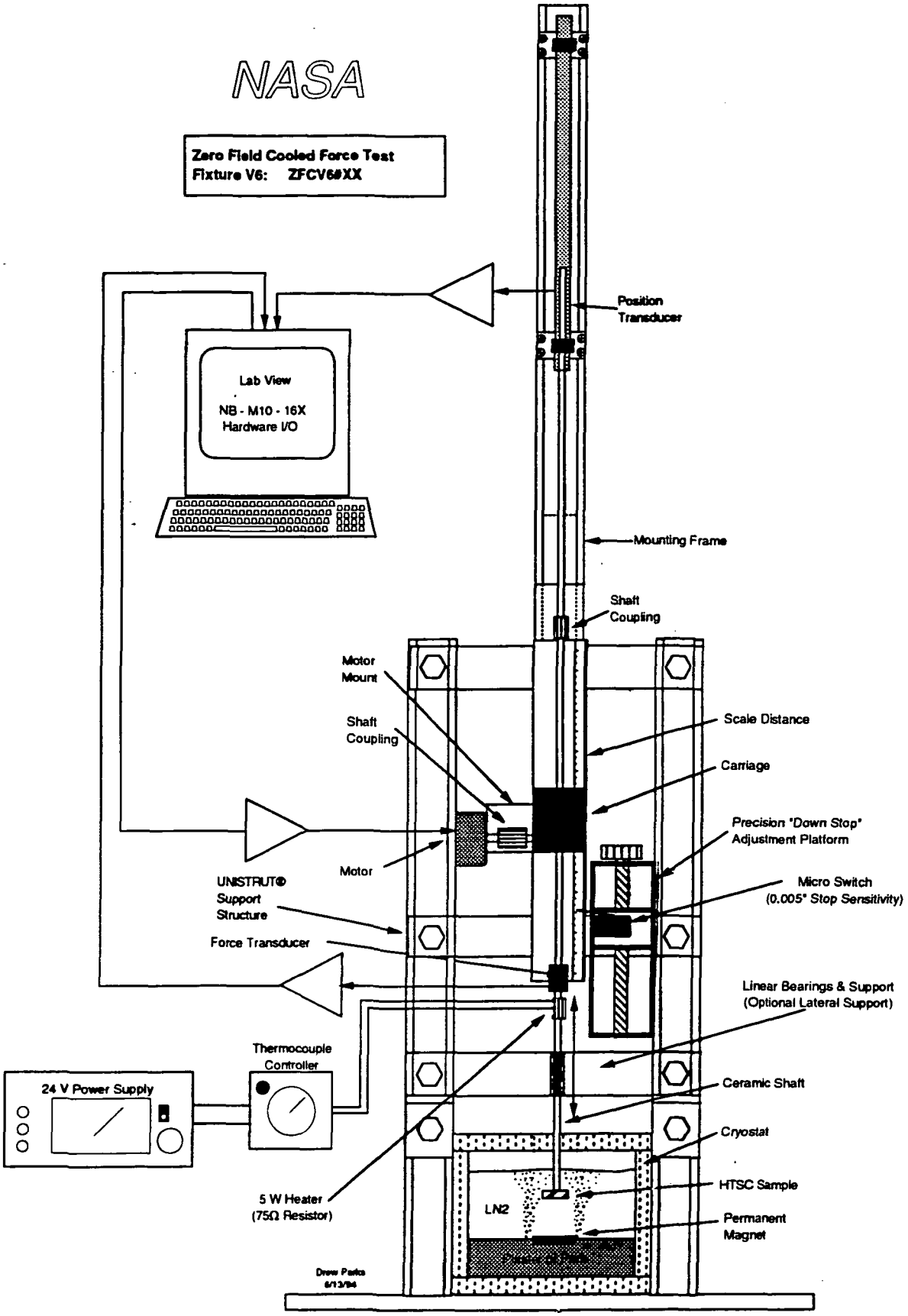


Fig.7. Bumper-Tether Test Rig

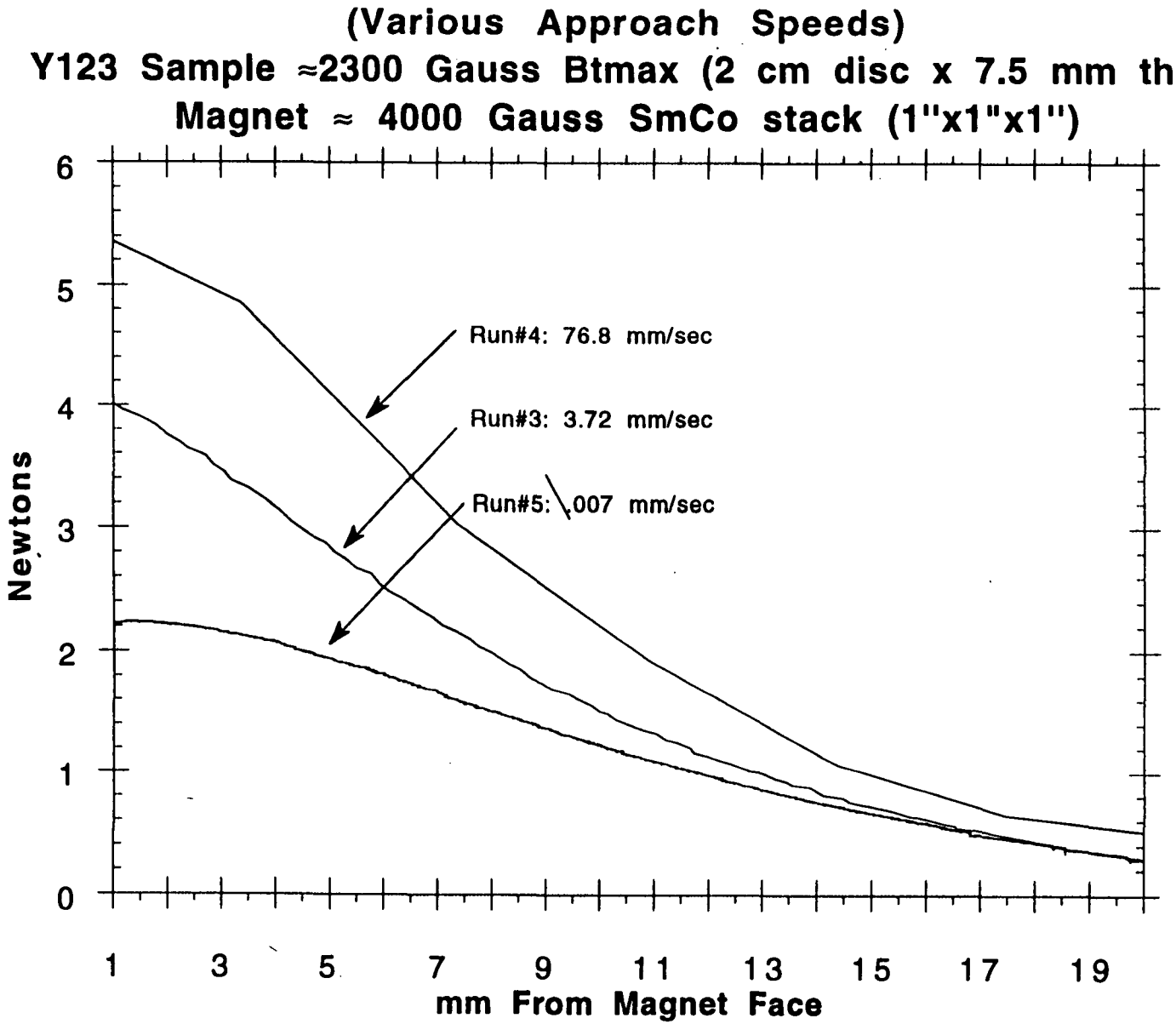


Fig. 8. Velocity Dependance of Bumper Force

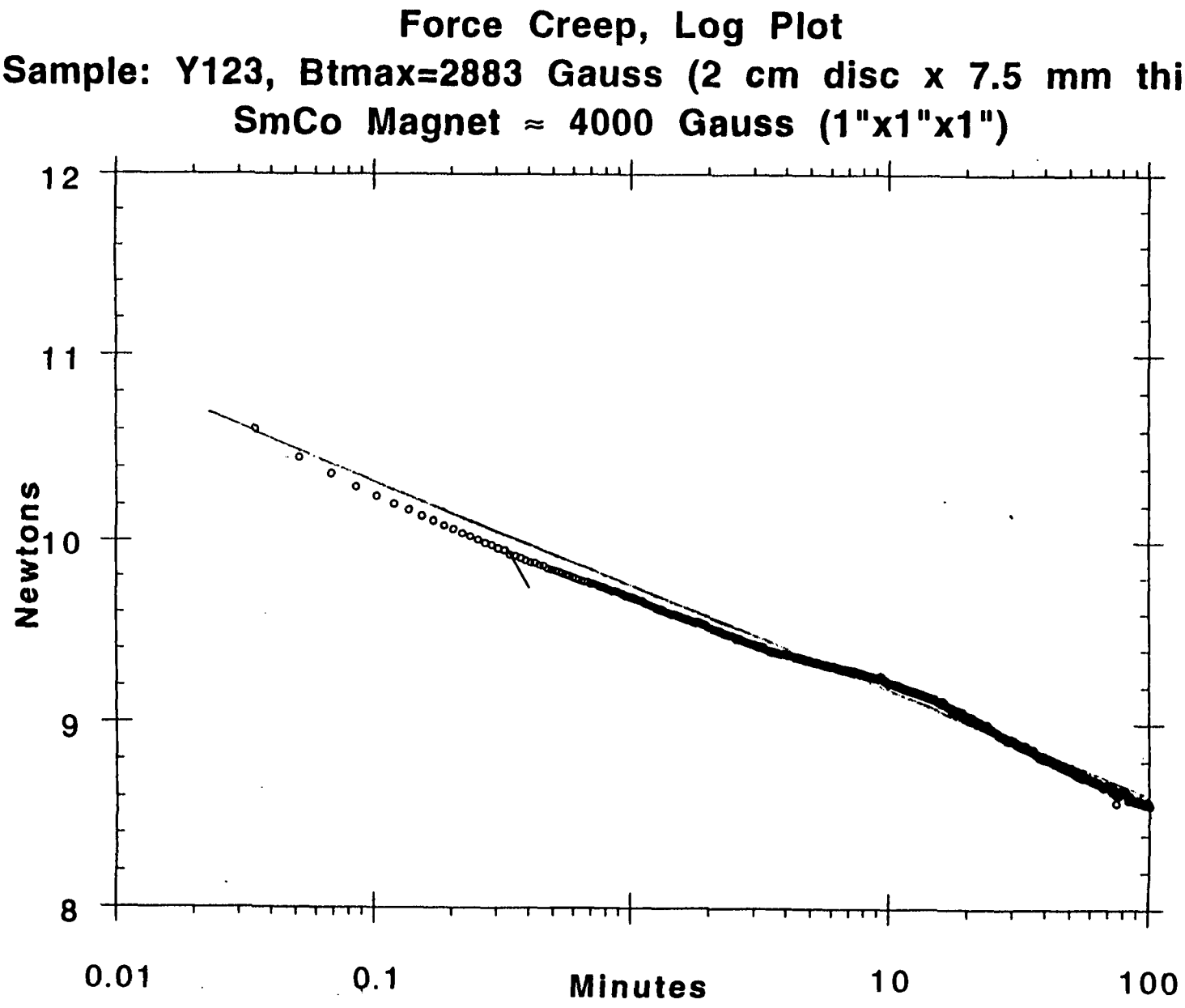


Fig. 9. Creep Measurement of Bumper Force